SILVA BALCANICA

Silva Balcanica 24(1): 55-68 (2023)
doi: 10.3897/silvabalcanica.22.e97620

RESEARCH ARTICLE

Short review of collecting technologies and methods in forest harvesting residues recovery

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Academic editor: Ivailo Markoff | Received 16 November 2022 | Accepted 06 March 2023 | Published 22 March 2023

Citation: Ghaffariyan M.R. 2023. Short review of collecting technologies and methods in forest harvesting residues recovery. Silva Balcanica 24(1): 55-68. https://doi.org/10.3897/silvabalcanica.22.e97620

Abstract

Tree felling and processing can create harvesting residues including leaves and twigs (needles), cones, barks, and branches. Collecting forest harvesting residues requires application of suitable machines and working methods. This article is aimed at reviewing the published reports to identify new harvesting machines and working methods for recovering harvesting residues and the current gaps. The scope of review included published research reports/articles from 2017 to 2022 (last five years). This global review results showed that popular methods for residue collection are chipping residues at roadside/landing and integrated biomass recovery. Forwarder, cable yarder and in-field chipper are predominantly applied within various recovery methods depending on ground and stand conditions. Harvesting residues are one of the promising sources for bioenergy production which requires developing efficient and low-cost harvesting systems. Latest research findings indicate that piling harvesting residues by a harvester-processor can improve the collecting productivity by the forwarder within cut-to-length harvesting operations. Integrating residue biomass recovery with conventional timber supply can reduce the total supply chain cost by 2%. Researchers also recommend applying more climate-friendly technologies and focusing on developing new machines with lower fuel consumption and subsequent emissions. Future studies can focus on the following subjects; a) to determine the productivity and cost rates of various residue recovery systems, b) to develop and test technologies with lower fuel consumption rates and c) to find innovative solutions to utilize thinning materials and best practices to store and process biomass materials.

Keywords

Forest biomass, Timber harvesting, Residues, Recovery, Supply chain, Productivity

Introduction

Tree felling and processing can produce harvesting residues that include leaves and twigs (needles), cones, barks, and branches with diameter larger than 3 cm (Ghaffariyan, 2013). The forest harvesting residues might be left and scattered within the cut-over area when trees are felled and processed to logs at the stump using a cut-to-length harvesting method (CTL). When whole trees are processed/chipped at the landings or roadsides (Whole tree harvesting method (WT)) the harvesting residues are then concentrated in a small or large pile of slashes at the roadside or landing areas. Different factors can impact the quantity of harvesting residues including: applied harvesting method, equipment, product type, silvicultural regime, species, site, stand age, diameter at breast height (DBH), and stand quality. Previous research in pine and eucalypt plantations confirmed the application of cut-to-length harvesting method produced a larger weight of residues (104.0 green tonnes per hectare (gt/ha) without additional biomass recovery and 64.7 gt/ha with additional biomass recovery after sawlog/pulpwood extraction) than the whole-tree harvesting method (12.5 gt/ha) (Ghaffariyan, Dupius, 2021). There are some benefits in utilising the harvesting residues. Collecting forest harvesting residues can create suitable source for bioenergy, biochar and biofuel production (Thiffault et al., 2015; Thiffault, Brown, 2019), reduce fire risk due to reduction on fuel load, improve site establishment and planting phases and reduce the beetle attack hazard (Schnepf et al., 2009; Numazawa et al., 2020) and create further entrepreneurial opportunities (de Klerk et al., 2022). It is notable that biomass recovery might lead into substantial nutrient removals from the soils that should be considered to ensure sustainability of the forest areas. Visser (2018) stated that recovering harvesting residues might not be a profitable work however it can have the following benefits; a) reducing the accumulation of harvesting residues, b) improving operational efficiency and c) increasing post-harvest plantable area. Collecting harvesting residues can be operated as a separate harvesting activity to the conventional sawlog and pulpwood recovery or can be integrated with the conventional sawlog and pulpwood recovery called integrated biomass recovery (Spinelli et al., 2019).

International Energy Agency (IEA) Bioenergy, Task 43 provides technical support to different member countries on biomass supply chain management. This study was initiated as Task 43 was interested in conducting a global literature review to identify any knowledge gaps or unresolved challenges identified in forest harvesting residue recovery operations. This review report is prepared to detail the knowledge gaps and to make recommendations on future case studies or projects that can be supported by Task43. This article is aimed at reviewing the published reports on forest harvesting residue supply chain as an important part of biomass supply chain case studies. The scope of this review is focused on the published reports/articles from 2017 to 2022 (last five years) to collect the latest information on supply chain management methods of forest harvesting residue recovery.

Methods

To find the required literature for this review the following keywords in English language were used: forest biomass, harvesting, residues, recovery, supply chain and productivity. The electronic search engines such as Google Scholar, Scopus and Web of Science, Research Gate and Academia were used to find the literatures after 2017 - last five years - (note there were a few exemptions in publication year to make sure the review included sufficient data from diverse regions of the world). The review results were classified based on their region/country with a description of the applied forest residue harvesting work method and technologies. Work productivity was also mentioned for the case studies that provided such information. Relevant concluding remarks made by the international scholars were summarised in the conclusion section to provide an overview of take-home messages for the forest biomass users.

Results

America

North America

According to Jacobson et al. (2019) harvesting residues are piled near landing then chipped to the trucks (chip vans) to be transported to the pellet mills in Alberta, Canada. Khiza, Han (2015) studied the harvesting residue recovery from whole tree operations in Humboldt County, California. The stands consisted of 60 year-old even-aged coast redwood (*Sequoia sempervirens*), Douglas-fir (*Pseudotsuga menziessii*), western hemlock (*Tsuga heterophylla*), and tanoak (*Lithocarpus densiflorus*). Shovel logging was applied in slopes ranging from 3-37% (average of 22%) and cable yarding was applied on the slopes ranging from 0-50% (average of 31%). Shovel logging included a feller-buncher, John Deere 3554 shovel machine and a processor at the roadside. The cable logging operation consisted of manual felling by chainsaw, extracting by a Skagit GT3 swing yarder, loading by a Linkbelt 3400 Quantum loader and processing by a John Deere 892 with a dangle-head processor. In shovel logging, a loader collected harvesting residues in the cut-over unit and at the landing. In the cable yarding site, a modified dump truck was used to collect the harvesting residues as the residues in the cut-over unit were not accessible to the loader. Kizha, Han (2015) reported that 70% of produced harvesting residues were recovered in shovel logging operations. The recovery rate for the cable yarding site was 60%, which was slightly lower than shovel logging due to difficult terrain conditions.

South America

Numazawa et al. (2020) reported that for every tonne of stem (pulpwood or sawlog) production in Brazil there is a 0.6 tonne harvesting residue left on the sites. In the

Amazon under selective cuttings for every tonne of commercial wood production there are 2.5 tonnes of harvesting residues. Numazawa et al. (2020) indicated that this significant quantity of harvesting residues can be utilised for charcoal/biochar production. Their study was conducted in 13 different sites located in the State of Para in Brazil where harvesting volume ranged from 15 to 30 m^3 per ha. The harvesting residues were collected using forwarders and farm tractors in the study area. The harvesting residues with diameter larger than 10 cm were cut to smaller pieces (approximately 1 m-long sections) to be utilised for charcoal production (Figure 1).

Figure 1. Cutting buttress root to small pieces in Brazil (Numazawa et al., 2020)

Asia

Indonesia

Natural forests in Indonesia are harvested by selective cutting regimes. Chainsaw operators fell and process trees manually and then skidders are used to extract the timber using tree length harvesting method to the roadside to be debarked and loaded to trucks for transportation. Suhartana et al. (2022) conducted a trial in a natural forest harvesting operation in Central Kalimantan Province. The main species was Meranti (*Shorea* spp.) mixed with some other species. The Indonesian scholars indicated that

harvesting residues are produced when trees are debranched by chain saw at the stump and during processing and topping at the landing. Technical faults by the harvesting crew were the main contributor to having a large share of harvesting residues (35% of total harvesting volume) including stump, buttress, butt and branches. Suhartana et al. (2022) suggested recovering harvesting residues with proper timber quality for further usages in Indonesia but did not mention specific recovery techniques and machines.

Japan

After the nuclear disaster in Fukushima in 2011, bioenergy application has been highly extended in Japan. Japanese forest harvesting residues are estimated to be about 4-10 million m^3 per year including harvesting residues and thinning materials left on the sites and if the forest industry is reactivated then a larger volume of residues would be expected (Goh et al., 2020). The cut-to-length harvesting method (using harvester-processor and forwarder) is applied on flat terrains where harvesting residues are collected by the forwarders (Figure 2). Mountainous forests are harvested using the whole tree method applying yarders and tower yarders in Japan. Harvesting residues are mostly concentrated at the roadsides following tree processing that will be then chipped/ground for bioenergy purposes (Yoshioka, 2020; Matsuoka et al., 2021).

Figure 2. Extracting harvesting residues by a mini forwarder in Japan (Yoshioka, 2020)

Europe

Austria

In Austrian forests and plantations, trees are felled by chainsaws or harvester-processors with different levels of mechanization. Then trees are topped and processed into logs (sawlog or pulpwood). The harvesting residues are then collected and extracted using two machines including tractors equipped with trailers and forwarders. The

harvesting residues are then piled at the roadside/landing to be chipped by a truck mounted chipper to produce wood chips for bioenergy usage (Kühmaier et al., 2022).

Czech Republic

Integrated biomass harvesting using harvester and forwarder was tested in spruce stands (*Picea abies*) (L.) Karst.) in the South Moravia (Czech Republic) region by Pajkoš et al. (2018). The harvesting residues were piled by a harvester (Rottne H11c and John Deere 1270) and then collected using a forwarder (John Deere 1110D and John Deere 1110E) during sawlog and pulpwood recovery.

The integrated biomass approach resulted in an increase of the total operating time by 8% for the harvesting system due to the longer time spent by the harvester and forwarder to pile and collect the harvesting residues. This study confirmed that the average harvester's productivity was 35 m^3/PMH_0 (solid volume) for sawlog/pulpwood harvesting. When the harvester piled the residues then its productivity diminished to 23.5 m^3/PMH_0 (solid volume) for sawlog/pulpwood harvesting. The average harvester's productivity for piling residues was 16.4 m^3/PMH_0 (loose bulk volume). The forwarder's productivity averaged 25.7 m^3/PMH_0 (note that GMt was not reported) when the residues were pre-piled by a harvester. If the harvesting residues were not piled by a harvester and only left scattered on the site then the forwarder's productivity diminished to an average of 23.1 m^3/PMH_0.

Romania

According to Cataldo et al. (2022), one of the potential biomass resources in Romania could be the residues from agroforestry systems. Apple Orchards cover a large land area and require annual pruning which produces a considerable quantity of woody residues on the farms. Thus, the Romanian researchers tested an innovative solution including a forwarder (to collect and extract Orchard residues from the farm to the roadside), a stationary chipper to chip the harvesting residues on the ground and a telehandler loader to load the chips into trucks for transportation (Figure 3). Their study focused on the work performance of a HSM 208 F forwarder. The average forwarding distance was 830 m and a mean productivity of 21.8 loose m^3 of wood chips per PMH_0 was achieved.

Figure 3. Forwarder, chipper, and loader operating in Orchard residue recovery in Romania (Cataldo et al., 2022)

Sweden

Lacruz (2019) reported that harvesting residues are mostly produced during final cutting especially in the stands dominated by Norway spruce (*Picea abies*) (Routa et al., 2013). The integrated biomass recovery method is often applied to recover harvesting residues by forwarders equipped with special slash grapple to reduce the risk of soil contaminant introduction to the recovered biomass. Experience gained in Swedish forestry suggests that leaving harvesting residues to dry naturally for at least a summer season to reduce moisture content and enable inducing the nutrient-rich components of residues to forest soils (Pettersson and Nordfjell, 2007; Nurmi, 1999 cited in Lacurz, 2019). Moskalik, Gendek (2019) reviewed the European chipping studies and suggested leaving harvesting residues for a period of five to seven months to dry. Then harvesting residues can be chipped and delivered to the end-user points over economically feasible transport distance.

Roadside harvesting residues are usually processed into wood chips using forwarder-mounted chippers and chipper-trucks in Sweden (Eliasson, von Hofsten, 2017). Another alternative is to transport uncomminuted residues to a central yard or end-user to be chipped by stationary chippers to gain higher chipping productivity (Kühmaier, Erber, 2018).

Bergström (2019) introduced and tested three new harvesting systems for biomass recovery in young dense stands. These included FlowConv, FlowFix and FlowCin. FlowConv included a harvester-processor that was equipped with a new cutting, accumulating and bunching head, a forwarder for timber extraction and a truck for transportation of loose residues. FlowFix was the same as FlowConv but the harvester was also equipped with a bundling unit. FlowCin included a new biomass harvester that used a similar felling head and a second crane. The second crane was used to pass the felled trees to the bundle unit. Then the biomass bundles were collected and extracted to the roadside by a forwarder (Figure 4). Bundles were then loaded to a truck to be transported to the end-user. Empirical and simulation data were used to model the productivity and cost of the harvesting operations. Bergström (2019) indicated that FlowConv's supply chain costs were 6-29% lower than two other systems due to utilising an innovative and efficient felling head.

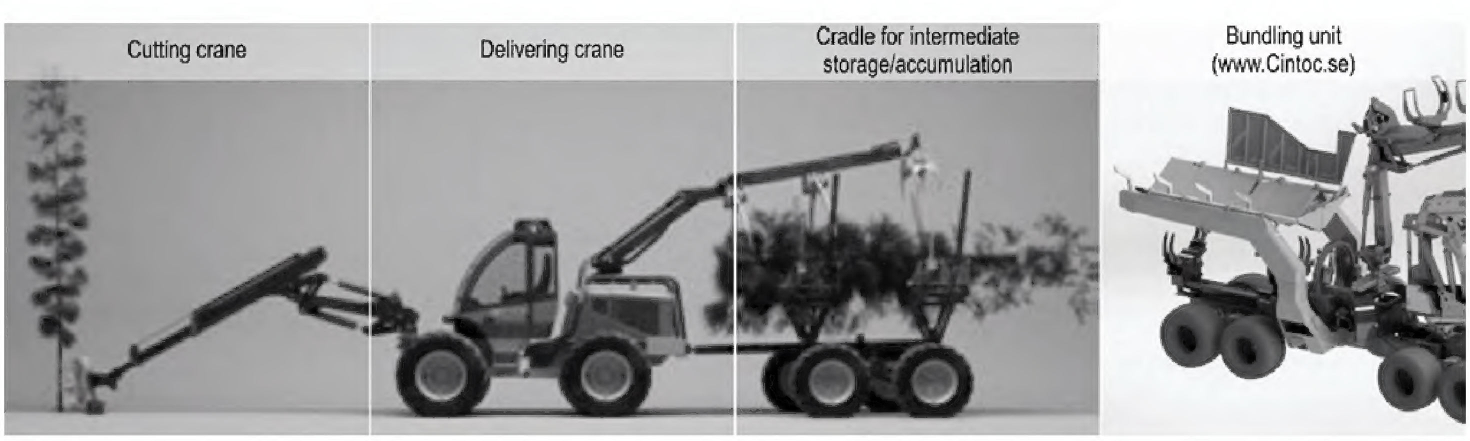

Figure 4. Bundler-harvester machine concept equipped with a delivering crane (Bergström, 2019)

Oceania

Australia

According to Martin, Cameron (2017) it is a cost-effective solution if a market can be developed for harvesting biomass residues that can also contribute to reducing fire risk. Two main types of biomass recovery methods were reported in Australian Pine plantations (Ghaffariyan, 2019). The first type was separate biomass recovery including a Pinox slash bundler and a Bruks mobile chipper. For both cases the stands were first harvested by cut-to-length method using a harvester-processor to fell and process the trees to short logs and a forwarder to extract the logs to the roadside. A Pinox slash bundler collected Eucalypt residues that were scattered on the site with a work productivity of 4.9 green metric tonnes per productive machine hours (GMt/PMH$_0$)) and a biomass recovery rate of 65%. The other method included pre-raking residues by an excavator then collecting and bundling by the slash bundler which was more productive (average productivity of 10.5 GMt/PMH$_0$). The Bruks mobile chipper mounted on a forwarder was tested in Victoria to recover harvesting residues from a pine clear felled plantation (Figure 5). The study was carried out within five study treatments. The treatments were: (a) collecting stem wood with minimum branches distributed over the site; (b) collecting only stem wood distributed over the site; (c) stem wood concentrated by excavator; (d) collection of all residues distributed over the site and (e) chipping residue logs at the roadside. The study revealed that when the machine was working on the roadside chipping residue logs into trucks, the machine productivity was the highest at 43.8 GMt/PMH$_0$. The estimated forwarding productivity to extract residue logs to the landing was 30-45 GMt/PMH$_0$. Biomass recovery ratio varied from 15.2 to 55% in the Bruks mobile chipper trial.

Figure 5. Bruks mobile chipper tested in roadside chipping in Australia

The Australian forest industry tested integrated biomass harvesting in pine plantations (*Pinus radiata*) which was proven to be an effective method. The residue logs (that did not meet the minimum length and diameter requirement of a sawlog or pulpwood) were collected during the sawlog and pulpwood recovery by a forwarder following harvester-processor operation. The reported work productivity for the harvester-processor and the forwarder for residue log recovery were 88.3 and 71.2 GMt/PMH$_0$ respectively (Table 1). Another method called fuel adapted harvesting was also tested in pine plantations harvested by combination of harvester-processor and forwarder within cut-to-length operations in Western Australia. In this method, harvesting residues were piled by a harvester-processor prior to being picked-up by a forwarder. This technique was found to be suitable for pine residue recovery as Strandgard and Mitchell (2019) reported a biomass recovery rate of 68%.

Fiji

Vuki, Visser (2020) described that Fiji's current harvesting system includes manual felling and processing into logs by chainsaw, mechanised extraction to the landing (skidding stems using rubber tiered skidders in plantations and bulldozers in native forests) and loading to trucks by the grapple loaders. The harvesting residues are produced in the cut over area (Figure 6) which is seen as a source of biomass to gain additional income for pine plantation growers. Vuki, Visser (2020) indicated that forest harvesting residues would be recovered by conventional and integrated biomass harvesting but did not provide further details.

Figure 6. Harvesting residues produced after tree processing in Fiji (Vuki, Visser, 2020)

New Zealand

According to Visser (2018) harvesting radiata pine plantations in New Zealand generates a significant volume of harvesting residues which is estimated to be 15% of the total timber harvesting volume. The harvesting volume is usually high in the areas with low market for short and/or small diameter logs and difficult hilly terrains due to higher rate of stem breakage during felling and extraction operations (Figure 7). Visser (2018) indicated that in New Zealand harvesting residues are generated following cut-to-length (scattered residues on the cut over area) or whole tree operations (concentrated residues on landings). It is preferred to extract the harvesting residues using bins to a stable location or apply an integrated biomass recovery method on steep or flat terrains. The harvesting residues can then be chipped or ground at the landing (Visser, 2018). On steep terrain (or steeplands as defined by Harvey, Visser, 2022) usually ground-based logging machines are not able to operate without significant earthwork or traction assistance, thus cable yarding or cable-assisted harvesting machines can be suitable alternatives to extract the timbers. The latest research findings show that the cable yarding operation leaves a larger volume of harvesting residues (110 m^3/ha) compared to the ground-based logging systems (68 m^3/ha) (Harvey, Visser, 2022). Road transport distances in some areas of the East Coast of New Zealand are around 200 km which requires upgrading the roads to enable using high productivity trucks. Also establishing the processing sites closer to the forests can reduce transport distance and costs (Hall et al., 2019).

Figure 7. Harvesting residues in cable yarding operations in New Zealand (Visser, 2018)

A summary of reviewed harvesting methods and their work productivity (where available) is provided in Table 1. Globally the popular harvesting residue recovery methods are: chipping residues at roadside/landing and integrated biomass recovery. Forwarders (on flat terrains), cable yarders (on steep terrains) and in-field chippers/grinders are widely applied machines within various recovery methods depending on ground and stand conditions (Table 1).

Table 1. Summary of forest harvesting residue utilisation case studies (note that some cases reported productivity in other units than GMt/PMH_0)

Continent/ country	Harvesting residue utilisation method	Machine/ model	Productivity (GMt/PMH_0)	Reference
America Canada	Chipping residues at landing/roadside	Forwarder, In-field chipper	n/a	Jacobson et al. (2019)
USA	Chipping residues at landing/roadside	Loader, Dump truck, In-field chipper	n/a	Kizha, Han (2015)
Asia Japan	Chipping residues at landing/roadside	Forwarder, In-field chipper/ grinder Tower yarder, Processor, In-field chipper/grinder	n/a n/a	Yoshioka, 2020 Matsuoka et al. (2021)
Europe Austria	Chipping residue logs at roadside	Tractor equipped with trailer Forwarder Chipper mounted on truck	n/a 20 m^3/PMH_0	Kühmaier et al. (2022) Affenzeller, Stampfer (2007)
Czech Republic	Integrated biomass recovery	Rottne H11c and John Deere 1270 Harvester John Deere 1110D and John Deere 1110E Forwarder	16.4 m^3/PMH_0 (loose volume) 23.1 m^3/PMH_0	Pajkoš et al. (2018)
Romania	Chipping farm residues at roadside	HSM 208 F series forwarder Jenz BA 725 Chipper	n/a	Cataldo et al. (2022)
Sweden	Small tree harvesting (whole tree including residues and stems)	Harvester with Bracke C16 head Forwarder	7.6 (OD t/PMH_0) n/a	Bergström (2019)
Oceania Australia	Chipping residue logs at roadside Integrated biomass recovery	Bruks 805.2 STC mobile chipper mounted on an Ecolog 594C forwarder Cat 541 with a Rosin RD977 processing head harvester-processor Valmet 890.3 Forwarder	43.8 88.3 71.2	Ghaffariyan (2019)
New Zealand	Chipping residue logs at roadside and integrated biomass recovery	Forwarder, In-field chipper/ grinder Tower yarder, Processor, In-field chipper/grinder	12-30 n/a	Visser (2018); Harvey, Visser (2022)

Conclusions and recommendations

Harvesting residues are one of the promising sources for bioenergy production which requires developing efficient and low-cost harvesting systems according to Japanese research findings (Yoshioka, 2020). Hall et al. (2019) recommended conducting further studies to determine the productivity and cost rates of recovering harvesting residues in both primary and secondary harvesting operations in New Zealand. Based on the

Australian experience of harvesting residue recovery, the slash-bundling method does not seem to be an economically viable option for low volume of concentrated harvesting residues as it can become an expensive machine when work productivity is low. The other issue is that considerable contaminants can be introduced into the bundles due to the application of an excavator. This could increase the moisture content (in the case of wet soil introduction) and might cause damages to the harvesting residue processing equipment. Future research can test the slash-bundler in large residue piles concentrated on the roadside/landing from whole tree processing operation (Ghaffariyan, 2019). Czech researchers recommended piling the harvesting residues by a harvester-processor during integrated biomass harvesting. This could help improve the work productivity of residue extraction using forwarders because shorter time was required to collect the harvesting residues when they were piled (Pajkoš et al., 2018).

Lacruz (2019) suggested that integrating residue biomass supply with a conventional timber supply can reduce the total supply chain cost by 2%. If the wood chips from different management areas are mixed to fill up the truck capacity, then we can achieve a 12% reduction in supply costs. Romanian scholars found that the combination of forwarder and chipper could be a considerable option to harvest orchard's pruning residues. The type of chipping and transport systems and their impact on overall supply chain efficiency could be subjects of future research. From emissions perspective, Kühmaier et al. (2022) concluded that wood transportation and timber extraction cause high emissions (accounting for 77% and 14% of the total emissions caused by timber supply chain respectively); hence, it is recommended to apply more climate-friendly technologies for biomass harvesting and transportation. Therefore, future research could focus on developing new harvesting and transport machines with lower fuel consumption and subsequent emissions. Future research could also test the impact of residues concentrations as biohubs and verify its impact on supply chain costs. Next studies can focus on biomass supply chain management in thinning operations and finding best biomass storage and processing practices and methods (including chipping and grinding).

Acknowledgement

This project was funded by IEA Bioenergy Task 43. The author would like to thank Prof. Mark Brown and the board members of Task 43 for their support.

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